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Microseismic Activity in an Open Pit Lignite Mine

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SYNOPSIS: An increased level of horizontal stress related to tectonic forces is often held responsible for unexpectedly strong mining induced seismicity. The authors use the Belchatow open pit lignite mine in central Poland to show that this seismicity can be explained without tectonic forces as well. The presented approach should offer affordable ways of detecting the problem before it occurs, and either preventing it or controlling its scale.

INTRODUCTION

Mining induced seismicity is common in many coal and hard rock mines. Mining induced seismicity associated with open pit mining is rarely observed.

Development of the opening cut for the Belchatow open pit lignite mine in central Poland started in 1976. The depth of the opening cut reached approximately 90 m (meters) when the first tremor of magnitude 3.6 occurred in August 1979. It was sensed by the crew on the dispatcher tower (Fig. 1), which experienced a series of swinging movements. Ground movements were also strong in a small building occupied by the mine hydrogeological team (Fig. 1). The spilling of a tea on the table marked the direction of

the horizontal displacement (generally to the southwest). In addition, cracks showed up in the walls inside the southern portion of the building. Ground motion also was sensed in the management building (Fig. 2), and by the residents of the nearby villages.

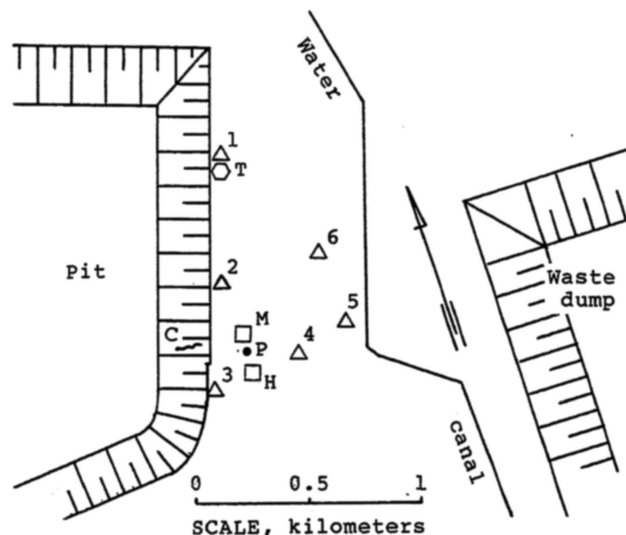


Fig. 1. Mining Situation and Elements Related to the Study on Seismic Activity. T-tower, M-monitoring station, P-piezometer, H-building, C-crack in slope, 1,2,3-geophones.

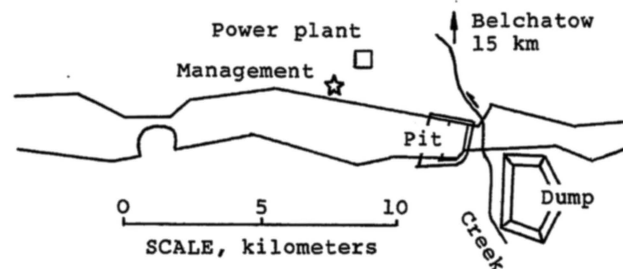


Fig. 2. Lignite Deposit in the Belchatow Trench.

The shock triggered concern about the nature of the activity, and a possible threat to the turbines of the power plant being constructed near the perimeter of the mine (Fig. 2).

The interpretation of the Belchatow case was published by Gibowicz et al. (1981, 1982), and Kijko (1983). This interpretation considered mining as responsible for disturbing an equilibrium in a "tectonically unstable, pre-stressed" horizontal stress system in the mine area. The interpretation was based on data from seismological observatories in Poland, Czechoslovakia, and a few central and northern European countries. These observatories were located more than 100 kilometers from the mine. Their ground movement recording instruments were designed for monitoring earthquakes in a frequency range below singular hertz.

Microseismic equipment was installed at the Belchatow mine site and the monitoring of microseismic activity began in the Fall of 1979. Location of the geophone array (Fig. 1) was selected based on:

- information collected from the witnesses of the first tremor,
- location of the opening pit and the waste (overburden) dump with respect to the local geological conditions,
- anomalies in the water table and vertical displacements of the ground adjacent to the pit contour.

Part-time monitoring and a number of breakdowns of the system resulted in incomplete recording or missing 11 out of 12 seismic events (magnitudes 2 and above) which occurred in 1980-81 (Gibowicz et al., 1981, 1982). All the weaker events often recorded by the system were not of seismic origin (sonic booms from jets). The epicentral location of the event of April 1980 (Fig. 1, magnitude 3.5) confirmed that the selection of the site for the geophone array was correct. It also was consistent with the model of the mining induced deformation process held responsible for the seismic events. Discussion of this model was presented to the Annual International Symposium on Geophysical Investigations in Mines held in Poland in September 1980.

The content of this paper relies on the author's recollection of his presentation and the experience at the Belchatow seismicity investigation. Study of published materials related to the subject also was helpful. The intention of this paper is to present another point of view as to the cause of the seismicity in the Belchatow case. It also emphasizes the importance of running an extensive dynamic analysis of the deformation and stress concentration process (induced by mining, in particular, geological conditions) for providing a reliable explanation of the observed seismic activity. This type of analysis is superior to considering seismic activity alone, with geological and mining situations as a static background. In each case, the choices of the monitoring equipment and array are fundamental for comprehensive study and reliable interpretation of data from mining induced seismicity.

GEOLOGICAL CONDITIONS

The Belchatow lignite deposit is located in the Belchatow tectonic trench approximately 15 km (kilometers) south of the town of Belchatow. The trench, 1.5 to 2 km wide and approximately 0.5 km deep, stretches east-west for over 40 km (Fig. 2). Southern walls of the trench are nearly vertical, and formed of limestone with karst (Upper Jurassic formation, Fig. 3). Cretaceous rocks, mostly sandstones and marls, border the trench from the north. Parallel faults shape these rocks into a series of steps gently dipping to the south. The bottom of the trench is lined with siltstones and claystones sometimes clayey sandstones of Lower Jurassic cut by a few parallel faults. The lignite deposit up to 150 m thick is covered by 100 to 200 m of overburden, mostly fine sands and argils with

lenses of boulder clays and silts (Fig. 3). Similar materials form the bedding sediments

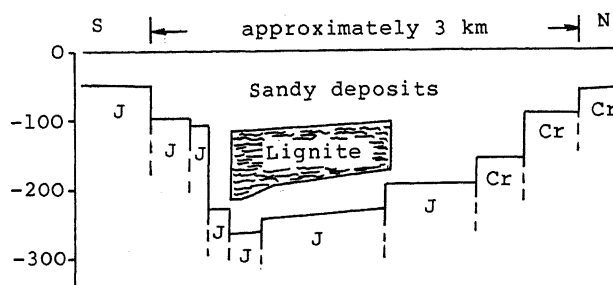


Fig. 3. Cross-section of the Belchatow Trench near the Area of Mining. J-Jurassic rock, Cr-Cretaceous rock.

down to the bottom of the trench. The deposit, 1.5 km wide in the area where the mining started, comes close to the southern wall of the trench. The northern edge of the deposit is separated from the northern side of the trench by a 0.5 to 1 km wide strip of Quaternary sands (Fig. 3). A map showing contours of the trench in the area of mining (reconstruction) is presented in Figure 4.

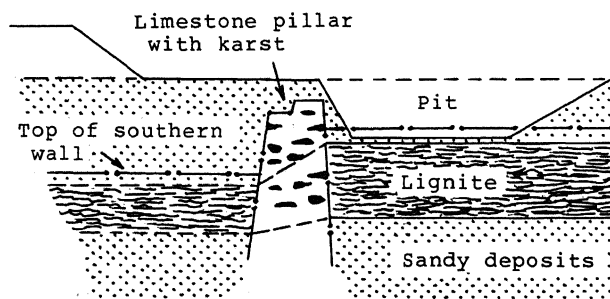
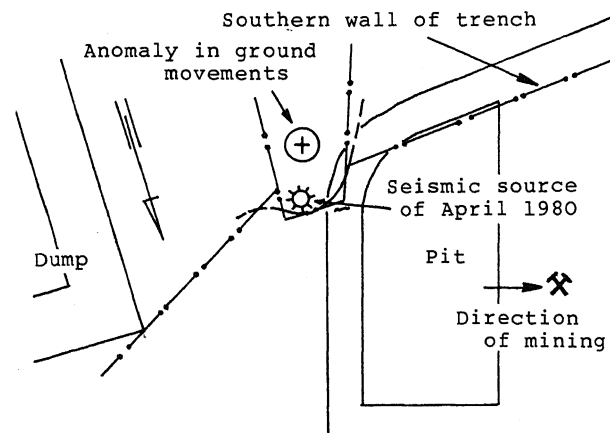


Fig. 4. Mining Situation with Respect to the Trench Morphology and Deposits.

Note the dislocation of the southern wall of the trench toward the north in front of the southeastern corner of the opening pit. Part of this wall adjacent to the pit contour is probably separated by a fault. It forms an uplifted limestone pillar with the top close (30-50 m) to the ground surface.

Permeability of the sandy sediments provides good hydraulic connections between all water reservoirs.

SEISMICITY AND INDICATIONS OF TECTONIC FORCES

Poland is situated far away from the tectonic hot spots of the globe. This does not exclude the presence of slowly varying weak or very uniform horizontal stress fields referred to as tectonic forces. The country sits over the transition zone between the Eastern European Precambrian platform to the northeast, and the Paleozoic platform to the southwest. Mountains along the southern border belong to two different orogenic formations. Local (in the scale of the globe) concentrations of tectonic forces are held responsible for rare and weak natural earthquakes in some locations along the southern border, and (much less) in central and north-eastern parts of the country (Olczak, 1962; Pagaczewski, 1972).

No earthquakes were reported in the Belchatow area in historic times. Based on the study of the vertical movements of the ground in Poland prior to 1975, the ground in the Belchatow area was sinking at 1 mm per year (Kielbasiewicz et al., 1982). Besides this information, the authors have no knowledge of any experimental data allowing assessment of the true level of the horizontal stress underground in Poland.

MINING SITUATION

The perimeter of the future mining (Fig. 2) follows the shape of the deposit. Dewatering in the mine area down to the lignite seam level started in 1975. The fine sands of the bedding deposits were left saturated with water. Figure 4 illustrates the contours of the opening pit and a part of the base of the waste (overburden) dump in 1979-80. Of the four slopes of the pit, the two parallel to the trench and the eastern slope were cut to the final angle of approximately 30 degrees. The slopes were formed mostly of sandy material. Only the bottom part of the southern slope was in the Jurassic limestone. There were no plants or grass cover which would provide any stabilizing action to the slopes. This also prevented masking surface failures as they occurred. The western slope was cut in wide steps as part of the advancing process of overburden removal. The bottom of the pit nearing the top of the lignite deposit in 1979-80 was from 90 to 110 m deep, approximately 1.5 km wide and 0.8 km

long (with respect to the trench orientation). Anomalous characteristics of slower subsidence next to the southern part of the eastern slope of the pit was related to the local bedrock structure (limestone pillar, Fig. 4). As remembered, the water table indicated a similar anomaly. There were no measurements of horizontal displacements at that time.

Dewatering of overburden probably resulted in removing water from many karst caves and tunnels in the limestone walls of the trench. In some cases, it could turn a hydraulic pressure into a depression. In each case, it should disturb the balance in a local stress system.

MICROSEISMIC MONITORING SYSTEM

A geophone array of six accelerometers was installed on the ground in front of the eastern slope of the pit (Fig. 1). A short period seismometer was installed side by side with the accelerometer (No. 3) for covering lower frequencies of the wave spectrum routinely recorded by seismological instruments. All transducers were oriented to respond to vertical components of the ground motion.

Accelerometers were installed in shallow holes; each was mounted on the top of a 1 m long fiberglass rod driven vertically to the full length into the ground for coupling. The seismometer was partially buried in the ground. Each hole was covered with a steel bucket, its bottom flush with the ground and capped with turf to reduce the noise from the strong winds. Signals from accelerometers were conditioned by preamplifiers and transmitted through shielded cables to the central multichannel FM magnetic tape recorder. Signals from the seismometer were transmitted directly to the recorder. Power for preamplifiers was provided from a car battery through an additional wire in each transmission cable. A loudspeaker allowed continuous audible monitoring of recorded signals. Magnetic tapes were replayed audibly and selected fragments of the record were reproduced with a stripchart oscillograph for the final data analysis.

Recording and reproducing equipment was adjusted for the frequency range from 0.5 to 375 hertz, with accelerometers covering from 10 to 3,000 hertz and the seismometer covering 0.5 to 30 hertz. An average sensitivity of the transducers was 0.015 V/m/s² for accelerometers and 400 V/m/s (volt per meter per second) for the seismometer. Dynamic range of recorded waves was limited by the tape recorder to 46 dB. The standard precision of the time reading was 0.5 ms (millisecond).

MICROSEISMIC EVENTS AND RELATED OBSERVATIONS

A number of weak events were recorded by the system. They were generated by sonic booms from jets. Double impulse character of their waveforms and uniform frequency were detected by accelerometers. These features were filtered to singular, low frequency, weak signals on records from the seismometer. Lack of small natural seismic events between strong tremors suggested a simple stress system and a uniform stress concentration process.

The epicentrum of the event of April 1980 (magnitude 3.5) was located over the uplifted limestone pillar (Fig. 4). The dominant wave frequency detected by accelerometers was approximately 60 hertz. The dominant frequency recorded by the seismometer was approximately 12 hertz. The event was accompanied by a crack in the eastern slope of the pit almost matching to the source location. In addition, the bottom of the piezometer well near the epicenter (Fig. 1) was damaged.

Moreover, the ground deformation associated with tremors was of concern in our study of the Belchatow case. Based on published materials (Kielbasiewicz, 1982), the deformation of the ground which accompanied the first tremor was interpreted as a superposition of two types of deformation (Fig. 5a, b):

- Loose material flow toward the pit as a result of a stress relief both in vertical and horizontal direction. This flow was controlled by the trapezoidal shape of the pit and the shape of the trench.
- A powerful displacement of loose material below the lignite seam directed to the northwest. This displacement resulted in relative sinking of the ground adjacent to the southeastern corner of the pit, and strong upheaval around the northwestern corner.

DISCUSSION

The common product of an investigation of mining induced seismicity is a retrospective model of the deformation process which has led to structural failures accompanied by seismic phenomena. While developing the model, all available data and observations allowing reconstruction of significant steps in the deformation process should be considered. The model should allow reliable prediction of the trend in the development of seismic activity, and should give clues as to how the problem can be corrected if necessary.

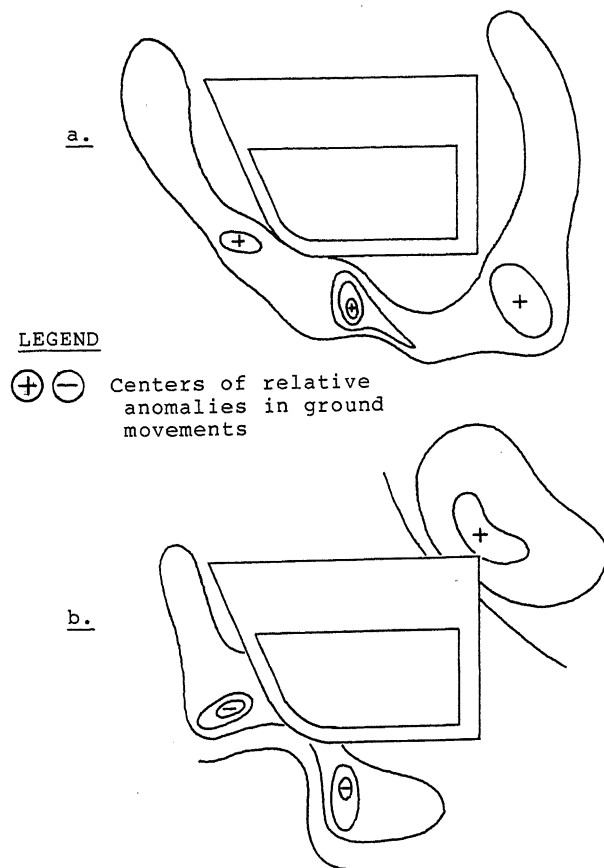


Fig. 5. Idealized Anomalies in Increments of Ground Vertical Movements: a. forced by stress relief in the trench; b. after a tremor.

The Nature of Mining Induced Seismicity - A Model

Dewatering of overburden around the pit resulted in a thicker layer of drained but still wet sands above the water table, and a drop in hydrostatic pressure in the remaining water saturated sands down to the bottom of the trench (Fig. 6). The subsequent shift from plastic toward elastic behavior improved the stability of loose material in the trench as a result of higher cohesion, and an increase of effective stress. A reduction of the load caused by dewatering upon the trench bottom and walls was considered insignificant.

Removing large amounts of overburden from the opening pit and storing them on the waste dump resulted in a substantial change in the distribution of vertical load.

An increase of load from the waste dump outside the trench (Figs. 2,4) should not affect deposits in the trench directly. However, some concentration of horizontal stress in

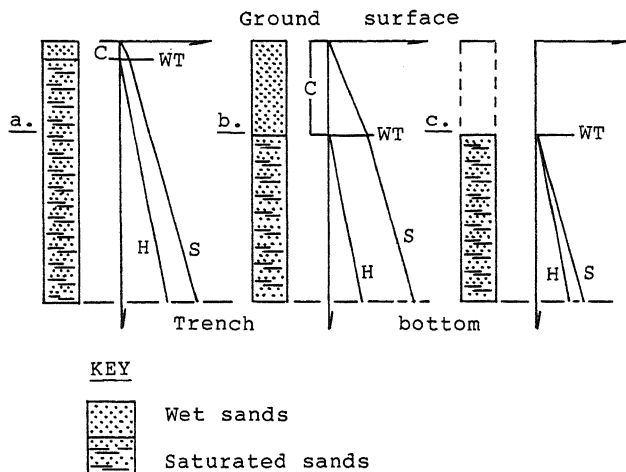


Fig. 6. Changes in Vertical Stress, Hydraulic Pressure, and Cohesion Zone in Loose Materials (a) as caused by Dewatering (b), and Overburden Removal (c). C-cohesion zone, H-hydrostatic pressure, S-effective stress, WT-water table.

the trench caused by the load from the dump could not be excluded. Nevertheless, the overburden removal was considered the major factor controlling both the vertical and the horizontal stresses within loose materials in the trench.

Horizontal stress relief should force a horizontal deformation of the surrounding material toward the pit. Flow of the material toward the pit should result in a concentration of stress, and possibly an upheaval of the ground surface in front of the pit corners and along the arch shaped zones facing each slope. The effect should be seen as anomalies in the vertical ground movements (Fig. 5a). Also, a general upheaval of the entire pit area should be expected. The upheaval phenomenon was observed since 1979 reaching the pace of up to 6 mm per year (Kielbasiewicz et al., 1982).

Mining operations inside the trench and the configuration of the pit with respect to the trench, should cause additional nonuniformities in stress. Flow of the materials from the west toward the pit should be relatively uniform, being continuously disturbed by mining advancing toward west at 400 m/year. The limestone pillar on the eastern side reduced a portion of the eastern slope exposed to the loose material flow from the east. This and the stationary character of the eastern slope resulted in developing a relatively stable stress zone in the loose materials east of the pit. This zone kept loose materials of the eastern part of the trench from flowing toward the pit. The stress zone was resting on the trench bottom and had relatively uniform support in loose

materials from the north (Fig. 7). The highest level of stress concentration (high shear stress) developed in the limestone pillar. Local centers of the stress concentration within this pillar and in the adjacent portion of the southern wall of the trench were expected to develop earlier as a result of draining water from karst caves and tunnels.

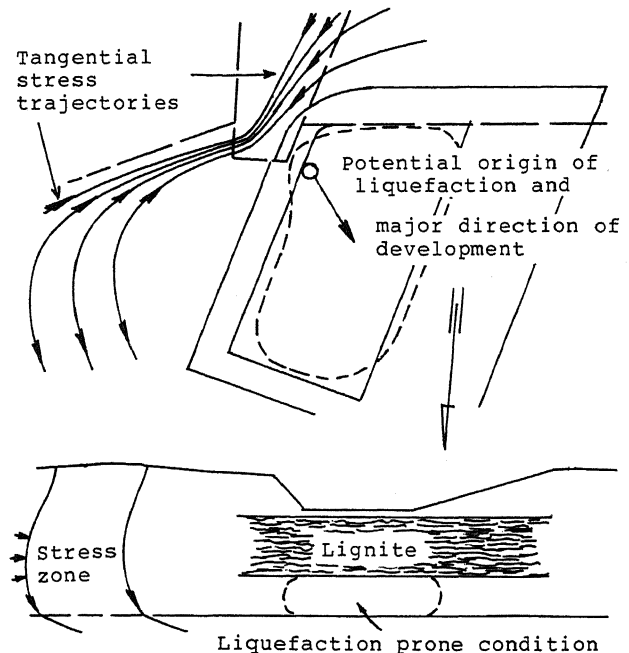


Fig. 7. Stress Zones and Liquefaction Prone Area Developed Around the Pit.

The stress concentration meant that even for a low average disturbance of stress caused by mining and dewatering operations at the pit, a local horizontal stress in the limestone pillar could reach considerable levels (Fig. 7). This could cause either collapse of individual caves or a shear failure within the pillar itself. Location of the event in April 1980 indicated the limestone pillar as the center of the stress concentration (Fig. 4). Failure in the piezometer well (Fig. 1) adjacent to the epicentral location was considered as related to the event occurrence.

Overburden removal gradually reduced a direct load upon the lignite seam and the bedding sands below the pit. Effective stress between grains dropped, while a free inflow of water maintained the hydrostatic pressure on a steady level. In the area around the lignite pillar, the obstructed flow of loose material from the east magnified the effect of the stress relief between sand grains, resulting in a condition prone to liquefaction (Fig. 7).

The energy released by any failure in the pillar should be absorbed by the stress concentration zone east of the pit. Considering

properties of the material, the large portion of this zone also should fail, resulting in a sudden massive load upon the liquefaction prone area. A hydraulic impact developing horizontally off the pillar area should force large amounts of loose materials to make a short (few centimeters) but powerful move toward the stress relief zone under the pit and up the slope of the northern wall of the trench. This should result in a strong secondary seismic effect (a phenomenon similar to the gas outbursts in coal mines). The ground surface around the pillar should drop while the upheaval of the ground surface adjacent to the northwestern corner of the pit should be expected (Fig. 5b).

Effects of this kind, with ground displacements on the order of a centimeter, were observed after the shock of August 1979 (Kielbasiewicz et al., 1982). Macroseismic effect from the strongest tremor which occurred in September 1980 (Gibowicz et al., 1982) also was directed to the northwest. In addition, the location of the crack in the eastern slope after the event of April 1980 (Fig. 4) was consistent with the surface effects expected to follow a failure in the pillar and a deformation which triggered a liquefaction.

Evaluation of the Total Energy as Dependent on Monitoring Equipment

According to the presented model, the stress system developed in response to the stress relief should be shallow and simple. A local stress concentration within the limestone pillar was directly attributed to the potential primary failure. When a failure occurred, the local stress structure absorbed part of the released energy. This resulted in seismic waves of proportional energy, and of frequency inversely proportional to the size of the stress structure and the wave velocity in the limestone (Brune, 1970). The size of the stress structure in the limestone during the event of April 1980 was estimated between 10 and 20 m (based on records from accelerometers). The frequency of 60 hertz was well above the range covered by seismological instruments.

A portion of energy released during a failure in the limestone pillar should be absorbed by the stress zone in loose materials next to the failure area. The large portion of the energy released when the loose material failed should contribute to the development of liquefaction. The liquefaction phenomenon should convert most of its energy into a powerful secondary seismic event. Large amounts of this energy should be radiated in the frequency range covered by seismological instruments. Consequently, proportions between the total energy involved during seismic event and the energy carried by seismic waves (frequencies below singular hertz) should be reduced from 100:1 (McGarr et al., 1979) to less than 10:1 (Duvall et al., 1967). This approach should result in a

considerable reduction of the estimated total energy released during each seismic event. Consequently, the energy disturbance caused by mining should be sufficient to justify the level of seismicity in the Belchatow mine.

CONCLUSIONS

The model presented in this paper gives another explanation of the nature of mining induced seismicity in the Belchatow mine. The explanation takes under consideration all available information regarding local conditions. This approach dictates largely qualitative character of the analysis in which relative increments are predominantly used.

The model does not require any high and unstable tectonic stress as a condition for seismic events of the observed magnitude to occur. This is consistent with the fact of no seismic activity in this area before the mining started.

According to this model, the conditions which contributed to the mining induced seismicity in the Belchatow case were:

- Fine and uniform sands of overburden as well as bedding deposits.
- Saturation of bedding deposits with water along with a partial sealing effect provided by the lignite deposit from the top and along the southern wall of the trench.
- Location of the lignite deposit in the tectonic trench formed of strong rock formations.
- Lowering the triggering level of liquefaction in bedding deposits as a result of an effective stress relief below the pit and within the limits of the protective stress concentration zone formed around the pit.
- Presence of the limestone pillar (possibly karstified) in front of the eastern slope of the opening pit.

All these factors formed a unique environment in which:

- the mining induced loading and unloading system destabilized the stress in the bedding sand deposits,
- stress concentration in the pillar resulted in local failures,
- waves generated by each failure triggered a massive failure in loose materials adjacent to the pillar,
- subsequent rapid increase of load triggered liquefaction below the lignite deposit,
- developing liquefaction resulted in a hydraulic impact polarized predominantly northwest toward the opening pit.

The scale and horizontal orientation of the hydraulic impact and its shallow location

were held responsible for very strong macroseismic intensity and its northwest orientation.

Seismic activity in the Belchatow area was interpreted as a temporary phenomenon related to mining in contact with the eastern slope of the pit. This activity should cease after the mining reaches the bottom of the lignite seam and moves to the west. In the meantime, a periodic blasting in the limestone pillar at the location where seismic events originated should force more uniform flow of loose material from the east toward the pit. The blasting should eliminate subsequent major seismic events, or lessen their magnitude.

Testing the stress and pressure in which sands become liquefaction-prone should provide information confirming the presented model.

Regarding the instrumentation part of this study, the selection of microseismic monitoring equipment (widened frequency range) is considered fundamental for the comprehensive study on any mining induced seismicity. This is particularly true for shallow and open pit mining operations, and other engineering projects dealing with slopes.

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